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Remote Sensing of Aircraft Contrails Using a Field Portable Digital Array Scanned Interferometer

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Summary:

With a Digital Array Scanned Interferometer (DASI), we have obtained proof-of-concept observations with which we demonstrate DASI' capabilities for the determination of contrail properties. These include the measurement of the cloud and soot microphysical parameters, as well, the abundances of specific pollutant species such as SO_x or NO_x. From high quality hyperspectral data and using radiative transfer methods and atmospheric chemistry analysis in the data reduction and interpretation, powerful inferences concerning cloud formation, evolution and dissipation can be made. Under this sub-topic, we will integrate DASI with computer controlled scanning of the field-of-view to direct the sensor towards contrails and exhaust plumes for tracking the emitting vehicles. The optimum DASI wavelength sensitivity range for sensing contrails is 0.35 - 2.5μm. DASI deploys on the ground or from aircraft to observe contrails in the vicinity. This enables rapid, accurate measurement of the temporal, spatial, and chemical evolution of contrails (or other plumes or exhaust sources) with a low cost, efficient sensor.

No subject inventions were made during this effort.

Introduction

Key macroscopic properties of aircraft contrails and microphysical properties of their constituent particulates, especially ice crystals may be defined precisely by application of novel remote sensing via hyperspectral imaging interferometry. We describe preliminary feasibility studies that demonstrate the value of our sensor as it might be applied for ground, airborne, and satellite-based coordinated measurements with other remote sensing methods. The proposed approach applies a hyperspectral stationary interferometer to acquire hyperspectral remote measurements of solar scattering from aircraft contrails and their surroundings. Preliminary description of feasibility measurements show that a range of new parameters for contrails are obtainable. These data can improve the understanding of the formation and dissipation of subsonic contrails, for example, in the context of climate modification. The goal is to use our initial, positive experience to develop an optimized interferometer for the contrail measurement.

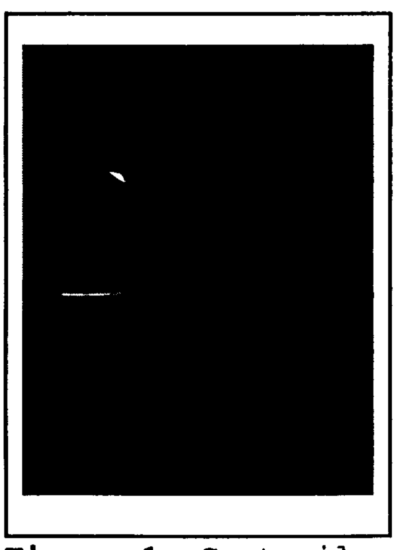

Figure 1. Contrail evolution for passing jet aircraft; Time = 0-18 seconds.

DASI is based on a stationary imaging interferometer which has highly desirable characteristics for contrail studies and for quantitative atmospheric radiance observations, including high throughput, high signal-to-noise, stability, insensitivity of calibration to base line offsets or drifts, and design simplicity and compactness, and their inherent fieldability.

Our work defined DASI' capability for the acquisition of radiometrically calibrated, medium spectral resolution hyperspectra of contrails with a wavelength coverage nominally 4000-12000 cm-1 (0.8-2.5 μm). We will utilize the data to improve present interpretive algorithms by their extension to automatic analysis of aircraft contrails to retrieve contrail properties from the measurements using radiative transfer codes.

Motivation for the Proposed Effort

The potential for aircraft contrails to have a climatic impact is a matter of current concern, and has motivated a number of recent investigations (Schumann, 1990; Gayet et al., 1993). Among the most important concerns is how and to what extent atmospheric radiative properties are modified by aircraft emissions of water vapor and aerosols. The radiative effects of the resulting formation of contrails and the possible increase of cirrus cloud densities are of particular interest. These investigations clarify the current state of knowledge of contrail radiative effects. The evidence suggests that contrails which persist at cruise altitudes consist primarily of ice crystals, and that ice formation from the initial engine exhaust stream occurs within a few seconds (Grassl, 1990). The evidence is based on thermodynamic arguments that the ice phase is favored even without any condensation nuclei (temperature below -40 C) and measurements of spectral transmission through the contrail. An example of the DASI data in Figures 1 and 2 is in agreement with this impression. There is evidence that contrails consist of much smaller ice particles than natural cirrus clouds (Gayet et al., 1993). This evidence is consistent with the particle formation conditions: rapid cooling of warm, moisture laden gases and an enhanced abundance of condensation nuclei (i.e. exhaust aerosols) would favor the formation of a large number of small particles. The engine emissions consist almost entirely of H_2O vapor and CO_2 (Grieb and Simon, 1990). The amount and location of injected water vapor

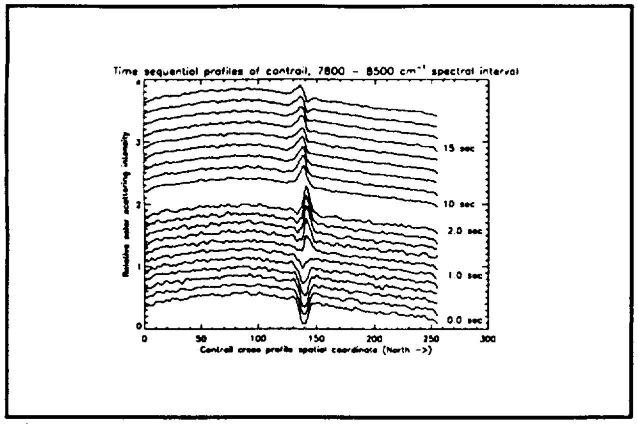

Figure 2. Contrail radiance profiles at 0.2 second and then one second intervals following aircraft passage.

available to form ice crystals can be predicted from information in specific aircraft flight trajectories, fuel type and consumption during flight, and ambient atmospheric conditions.

Assuming the availability of specific information about aircraft flights and the local atmosphere, the greatest uncertainties for predicting the radiative effects of contrails are a lack of knowledge of emitted condensation nuclei (CN) and the resulting ice crystal characteristics. The CN ultimately affect the ice particle concentration and size distribution. These particle attributes are important in determining single-particle scattering properties such as albedo and scattering phase functions. Both size and shape of particles are important parameters in the radiative properties of ice clouds (Takano and Liou, 1989). The ice crystal size is also a major determinant of fall-out velocity (Heymsfield, 1972). Thus, the radiative and physical transport characteristics of the ice crystals may be substantially influenced by the CN emissions and subsequent crystal growth conditions in the contrail.

In practice, other considerations may contribute additional uncertainties in predicting the structure and evolution of contrails. Contrail lifetimes are dependent on lateral and vertical diffusion which is not only influenced by the dynamical and thermal structure of the atmosphere but also by aircraft and engine design (Grassl, 1990). Physical and chemical processes which occur within the first few seconds of emission may be important determinants of contrail effects because of the initially high concentrations of species and high temperatures. Having detailed spatial and spectral (compositional) information about contrails during their formation and evolution would help resolve many of these uncertainties. Remote sensing of the contrails via hyperspectra is, thus, a promising approach to address these issues.

Cirrus Cloud - Model Comparison Using DASI

We have obtained cirrus cloud measurements with DASI. The measurements were made using a configuration similar to that shown in Figure 3 with a spatial field of view of about 5 degrees angular width. Push-broom images were obtained by scanning a computer controlled mirror in front of the light collecting optics over the field of view, sweeping the image across the entrance slit.

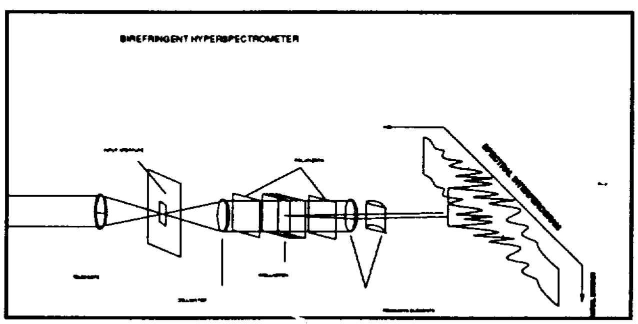

Figure 3. Birefringent Hyperspectral Interferometric Sensor.

SWIR measurements were made using a low-light level HgCdTe FPA (Kozlowski et al., 1990). The FPA has a wavelength sensitivity range of 0.8 - 2.5 μm and 256 x 256 pixels. A short-pass interference filter was placed inside the liquid nitrogen cooled dewar containing the array to block the thermal background radiation. The filter limited the spectral range to 0.85 to 2.2 μm. We selected a modest effective spectral resolution of ~40 for these studies. DASI' single frame rate was 5 Hz.

Summary of Measurement Results Enabled by DASI

The hyperspectra, coordinated with radiosonde, lidar, aircraft, and satellite measurements will enable the accurate determination of:

- Spatial extent and time evolution of the contrails
- Spatial distributions - mapping of variations in aerosol optical properties
- Particle composition and phase from spectral signatures
- Extinction optical depths of particles
- Scattering phase functions of particles
- Particle sizes (for size ranges up to a few times the maximum detected wavelength)
- Accounting for spectral effects of atmospheric path (observer to contrail), particularly important for ground measurements

There are ancillary studies and information that may be obtained, including:

- Ground truth and satellite validation
- Information from the interpretation of aerosol scattering phenomena such as rainbows, halos and glories

Retrieval and modeling

The task of modeling scattered solar radiation from contrails is formidable. Generally, effects such as shadows (see Figure 1) and multiple reflections between different cloud surfaces and between clouds and the ground must be considered. We will continue to focus on the requirements placed upon the sensor by the optimum numerical approaches that may be used for selected measurement conditions where simplifying approximations may be made. The development of specific radiative transfer code is an essential follow-on. Some observation scenarios follow:

Optically thin localized or spatially diffuse hazes: The single scattering approximation for the haze particles is valid. The plane-parallel horizontal layer assumption will not be important. Under these conditions atmospheric absorption and haze radiative effects can be simulated using LOWTRAN-7 (Kneizys et al., 1988). We have found it necessary to make modifications to permit the input of high spectral resolution extinction, absorption, and asymmetry values for scattering particles. Localized single-scattering phenomena such as glories will require a more rigorous treatment of the scattering phase function (Spinhime and Nakajima, 1989).

Optically thick, localized contrails or clouds: The single scattering and plane-parallel horizontal layer approximations will generally be invalid. DASI may observe solar scattering from the side of the cloud or diffuse transmission through it. Under these conditions the optically clear parts of the optical path (i.e., sun to cloud and cloud to observer) can be modeled with LOWTRAN-7. The scattering of radiation within the cloud can be modeled using DISORT, a discrete ordinates radiative transfer code designed for multi-layered plane-parallel media (Stamnes et al., 1988). The coordinate system of the cloud layers can be tilted with respect to horizontal to approximate the cloud's actual geometry. DISORT can utilize non-spherical particle scattering phase functions.

Spatially diffuse clouds with moderate to high optical thickness: The plane-parallel horizontal layer approximation for the cloud particles is valid. The DISORT code can be used to model the entire atmosphere. This code can be used to calculate directional radiances more accurately than LOWTRAN under these conditions since LOWTRAN uses just a 2-stream treatment for multiple scattering effects.

The techniques described above can serve as the primary means of retrieving cloud properties from DASI hyperspectra. Quantities of interest include scattering phase functions, size distributions, cloud optical depths, and all their spatial variabilities.

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